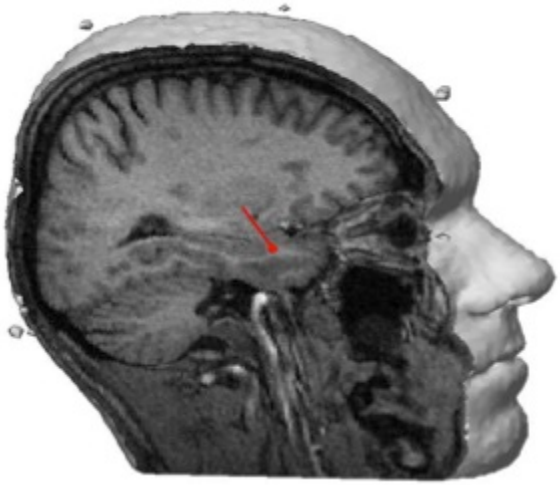
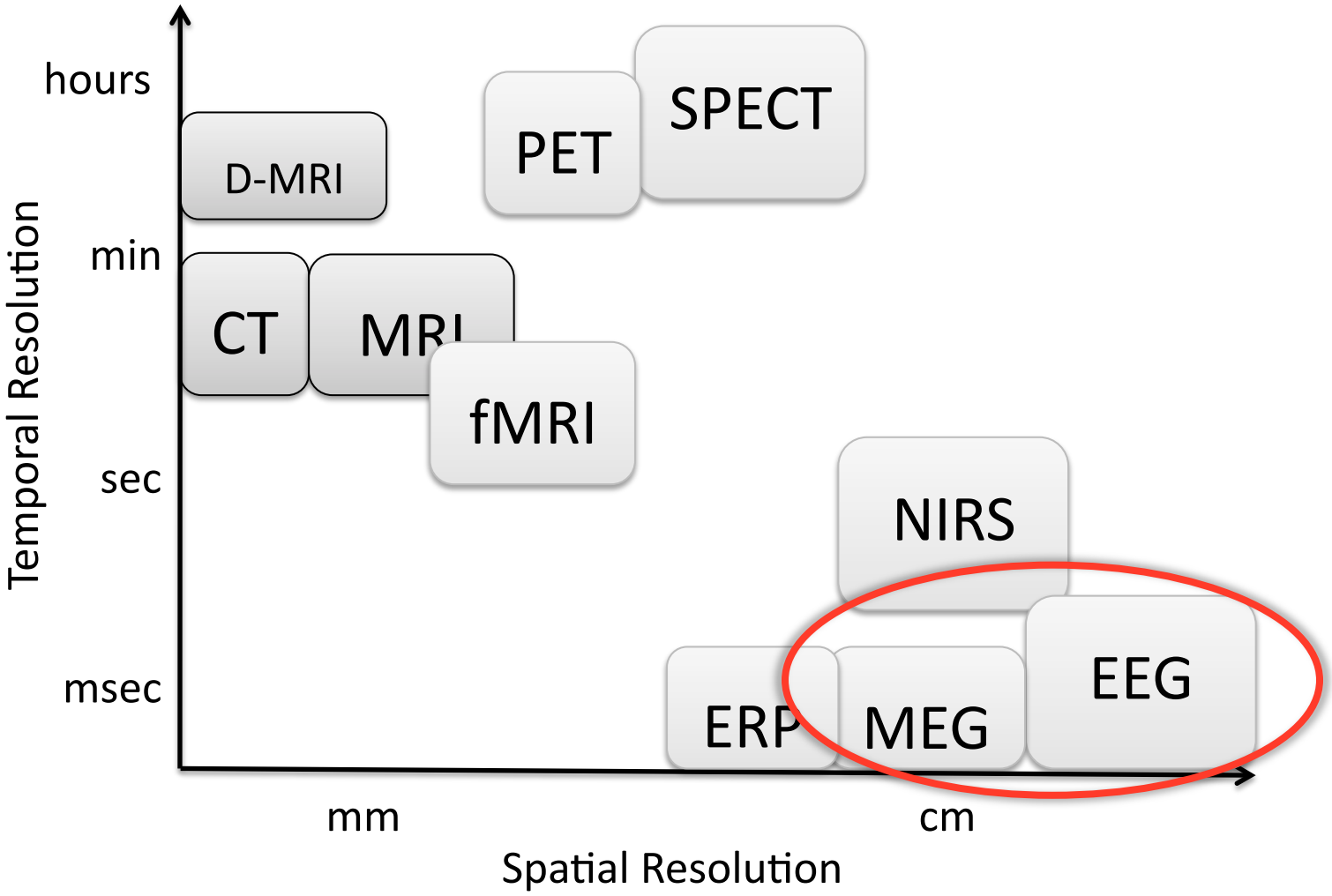
# Brain Imaging through EEG and MEG

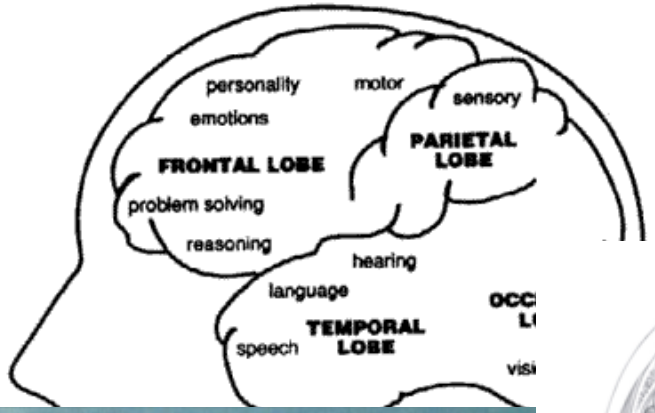
Dr. ir. Hans Hallez

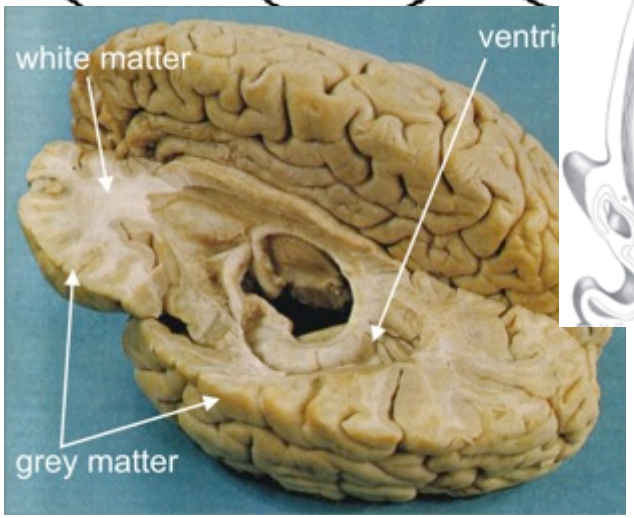


# Imaging the brain

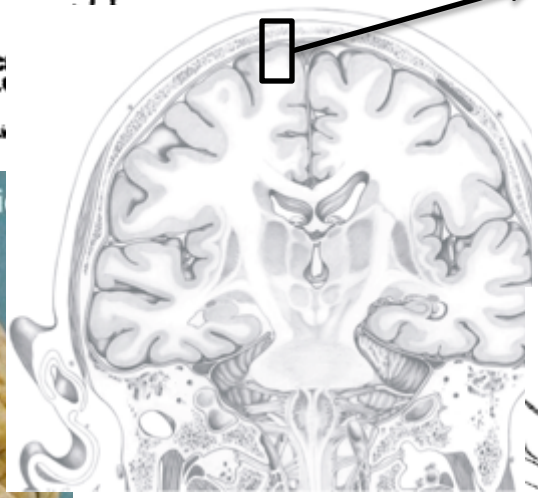


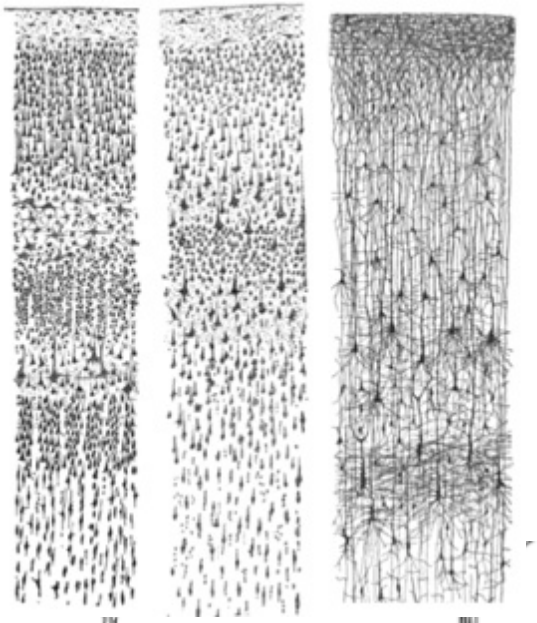
# Neurons as electrical generators

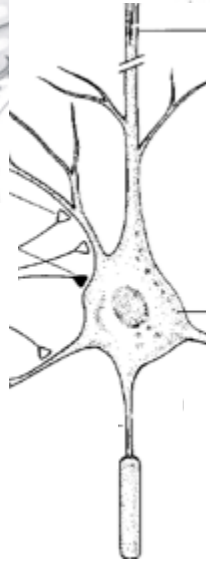


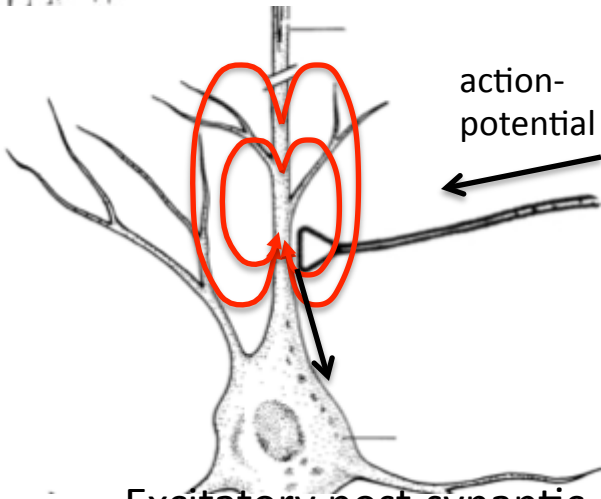




Grey matter



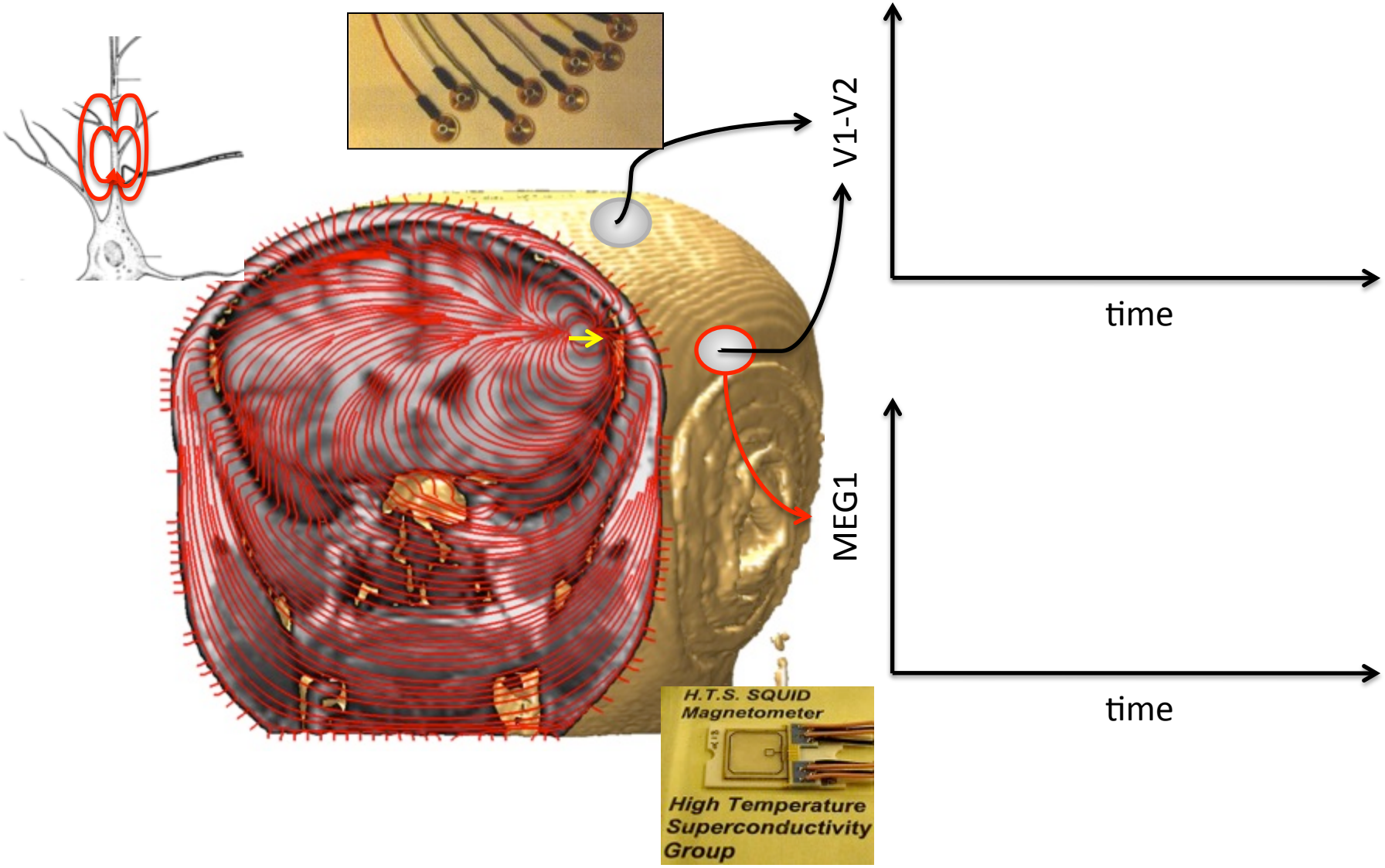




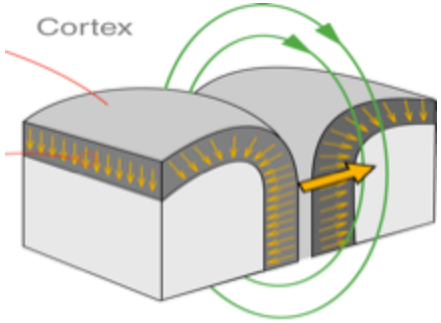


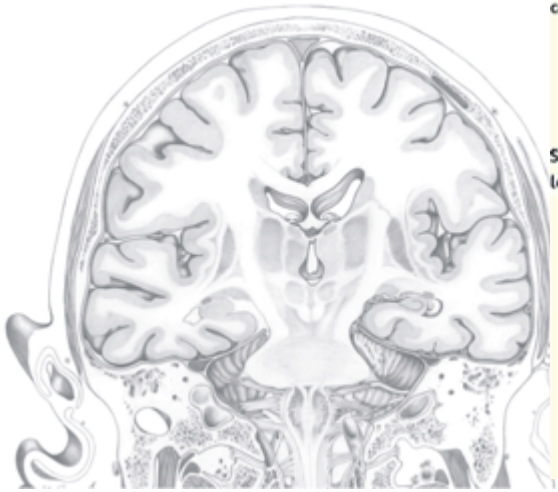

Excitatory post-synaptic potential (EPSP)

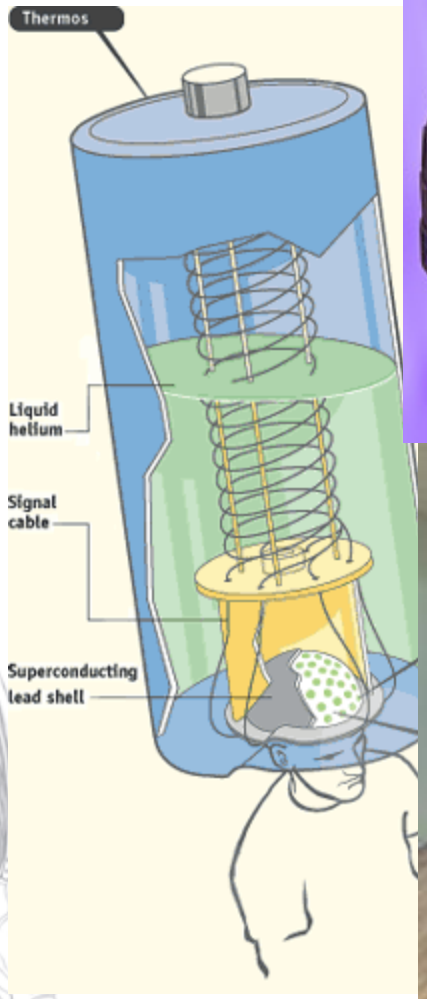
# Volume conduction



# Magnetoencephalography

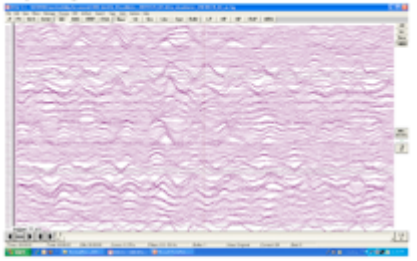


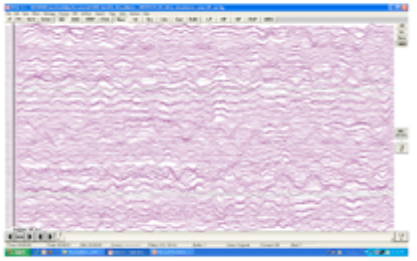



>300 sensors

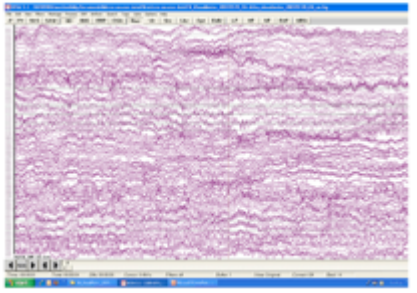
a) Eyes closed



b) Eyes open

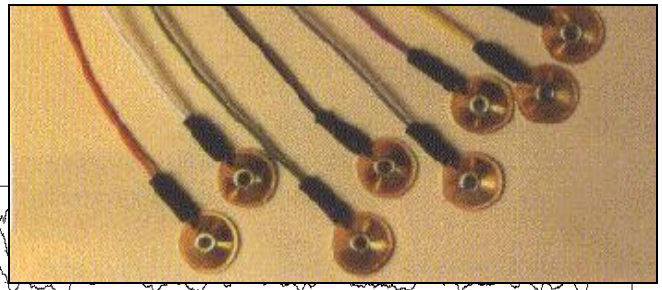


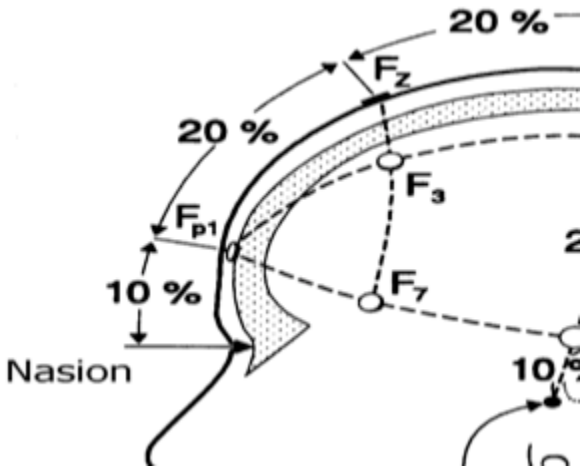
c) Looking at a computer

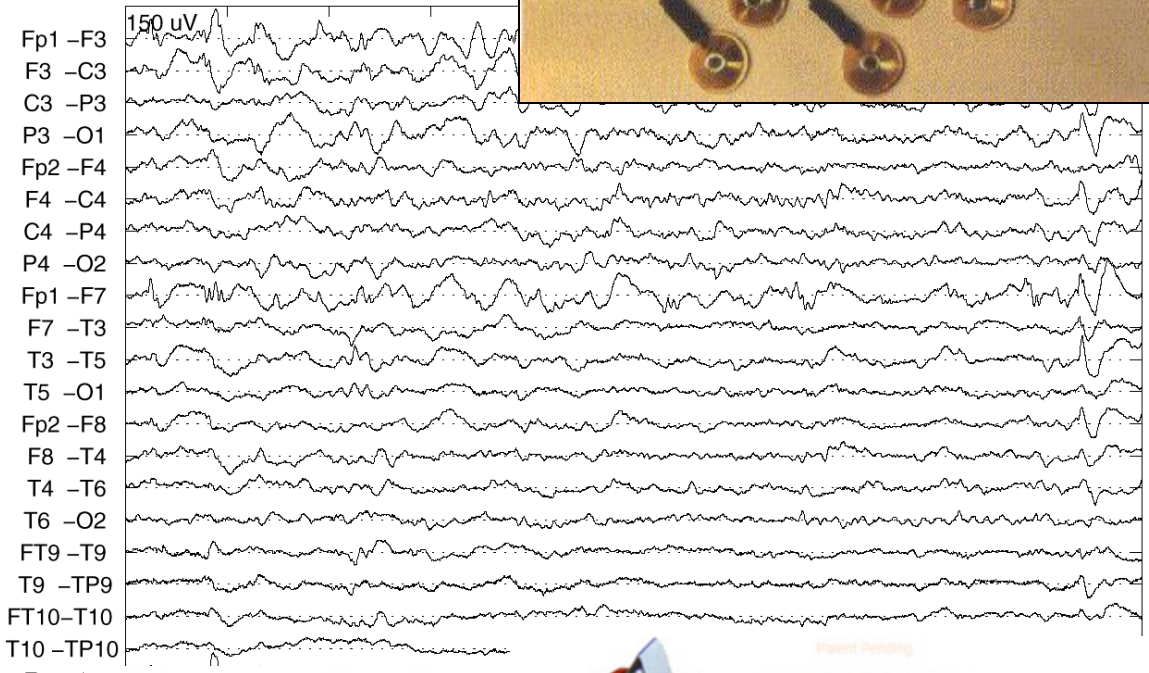


*[pictures courtesy of E. Carrette]*

# Electroencephalography

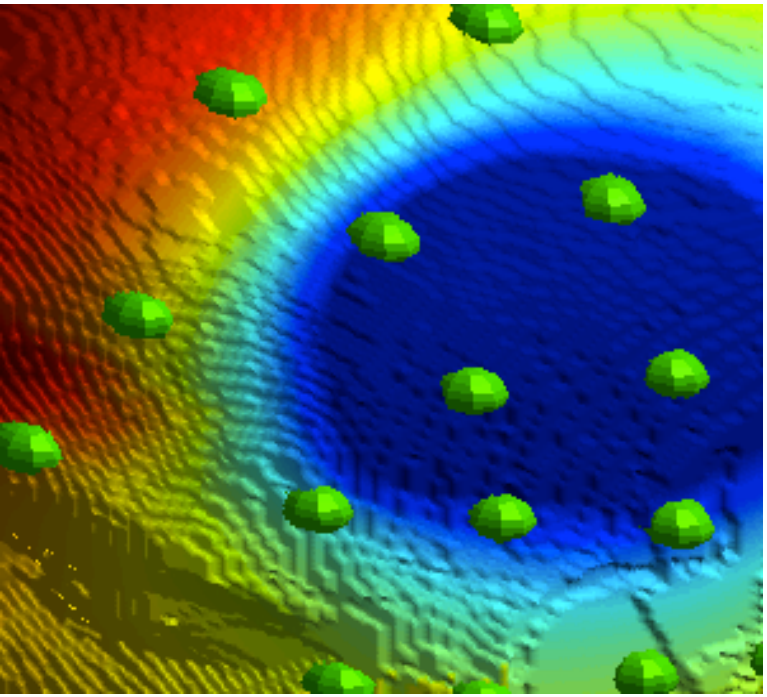




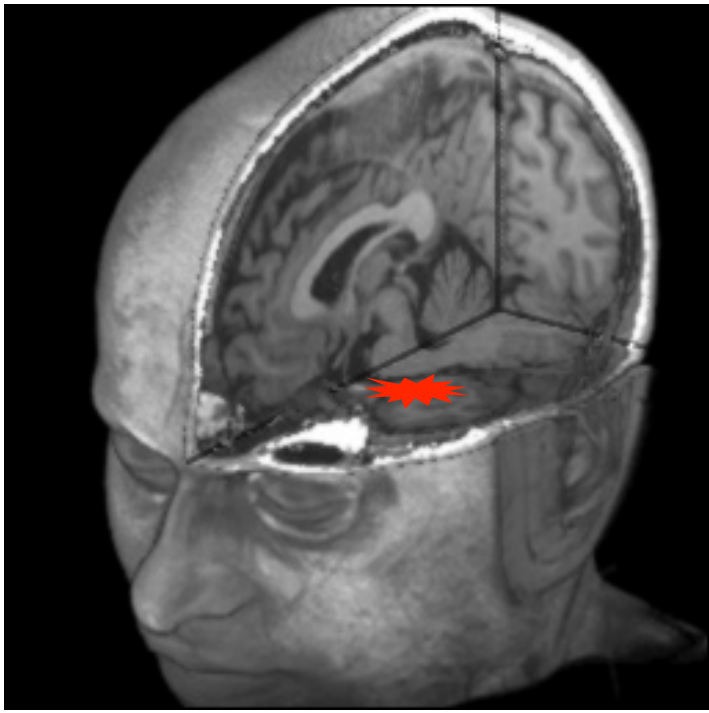




# EEG/MEG source localization

Potential distribution at the scalp measured at electrodes or sensors



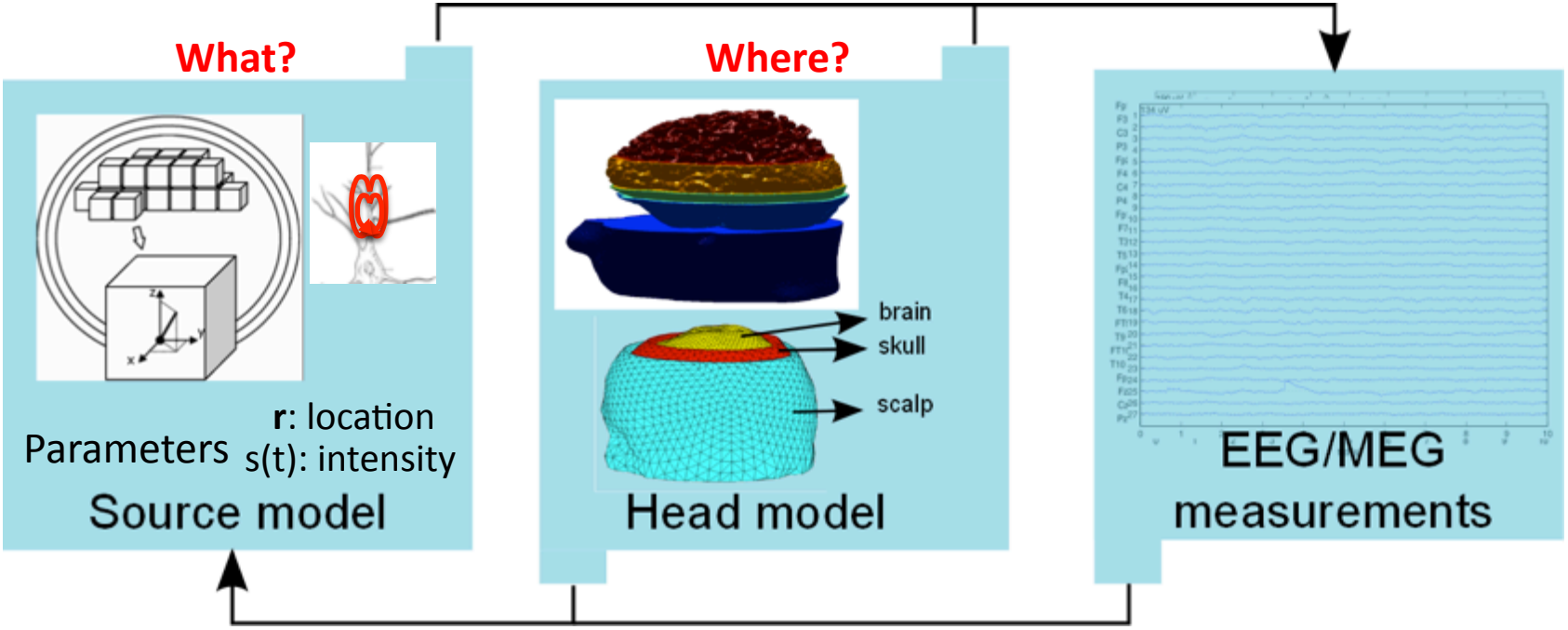
Estimation of the origin of the electrical activity in the brain



# EEG/MEG source localization

## Forward problem **How?**

Calculation of potentials or magnetic field
due to a source in a head model




## Inverse problem **How?**

Estimation of the source parameters
given the EEG/MEG and a head model

# EEG/MEG source localization

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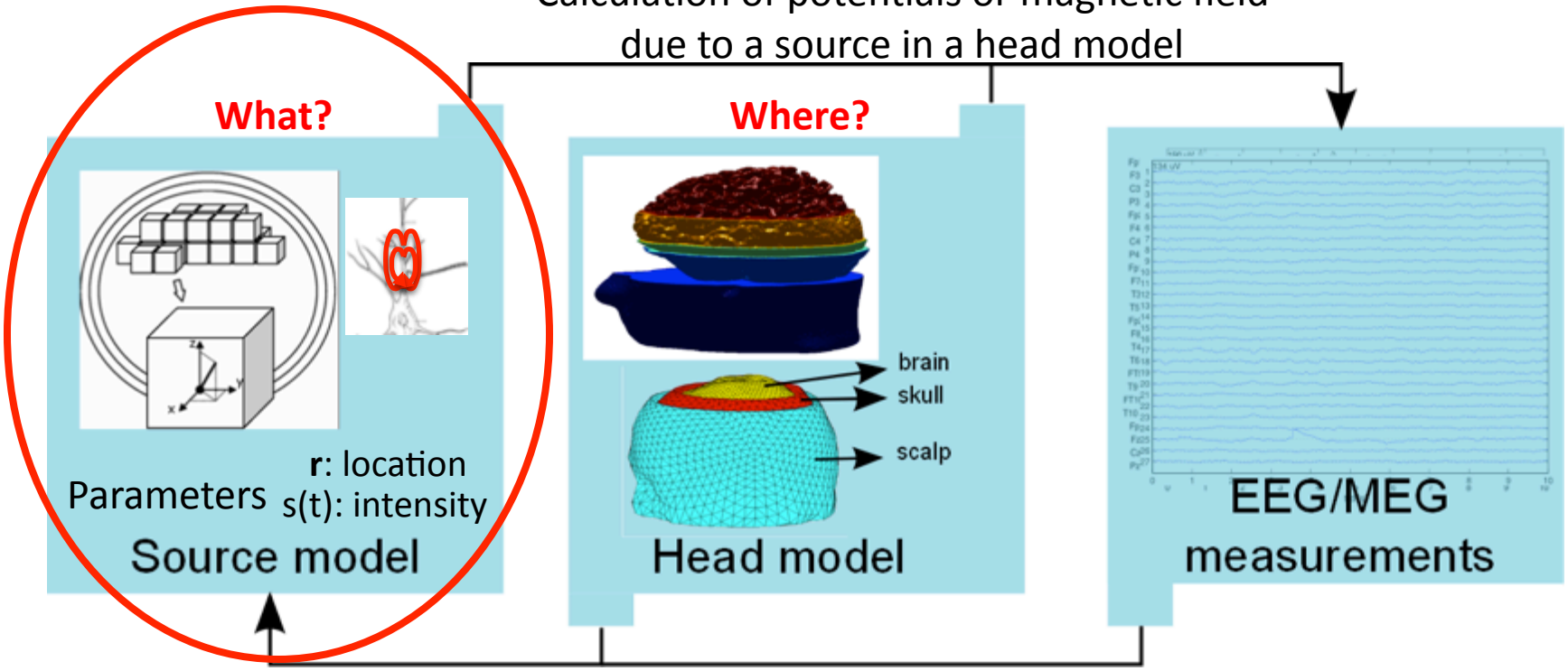


## Inverse problem **How?**

Estimation of the source parameters
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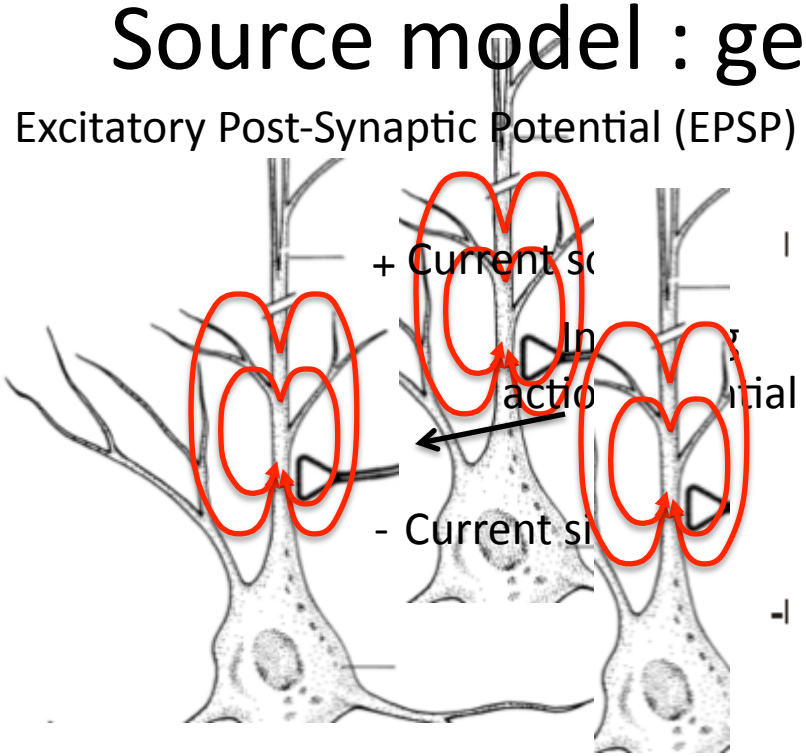
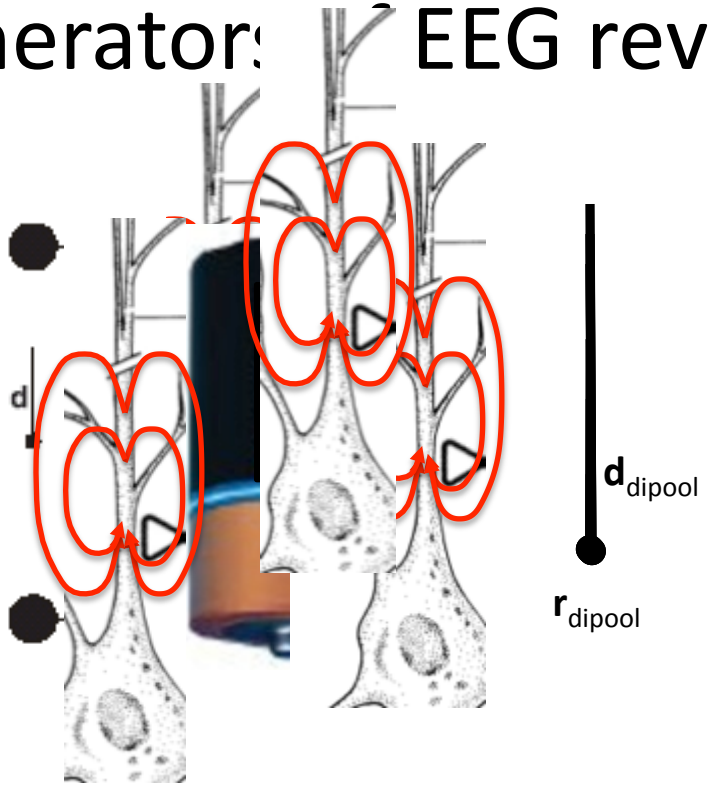
# Source model : generators of EEG revisited

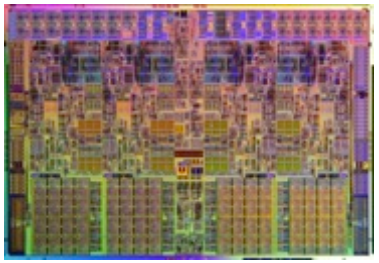
Excitatory Post-Synaptic Potential (EPSP)



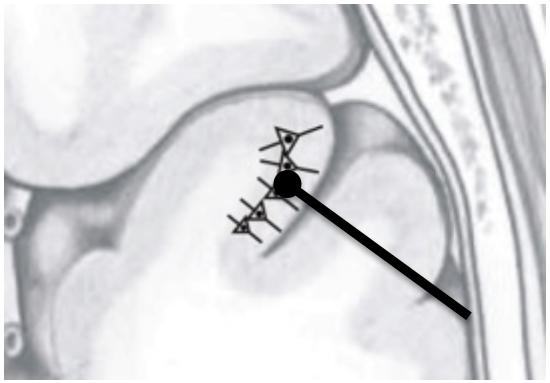



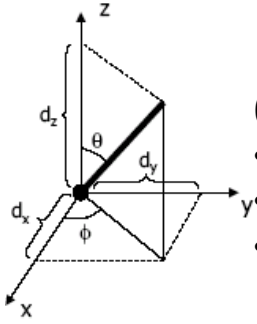

Microscopic current
due to 1 EPSP : **$5.10^{-5}$ nAm**

Macroscopic current measured: **50 nAm**
equivalent to a cortical patch of **5.5×5.5 mm²**



100 times smaller than the current
in a transistor on the Intel Core i7

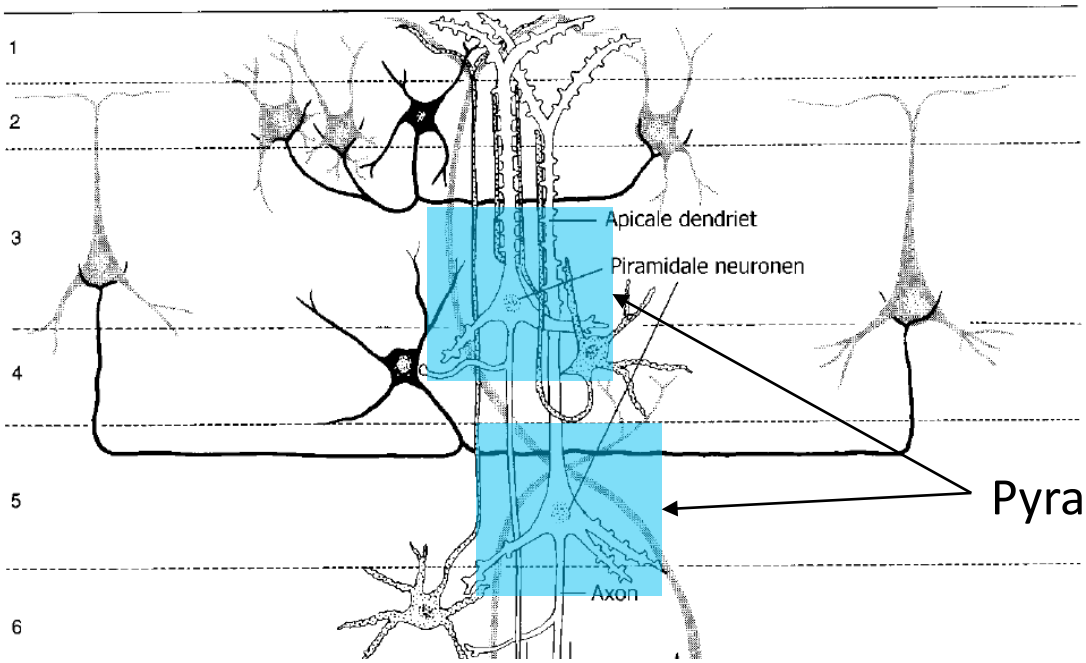





6 parameters
- Location **r** (x,y,z)
- Orientation : θ,ϕ
- Intensity : s

# Source model : generators of EEG revisited

- Superposition of *large group of synchronously activated* neurons required to produce measurable potentials at the scalp
- Pyramidal neurons
  - Long apical dendrites oriented in parallel, perpendicular to the cortex
  - Are believed to be the main EEG generators



# EEG/MEG source localization

## Forward problem **How?**

Calculation of potentials or magnetic field
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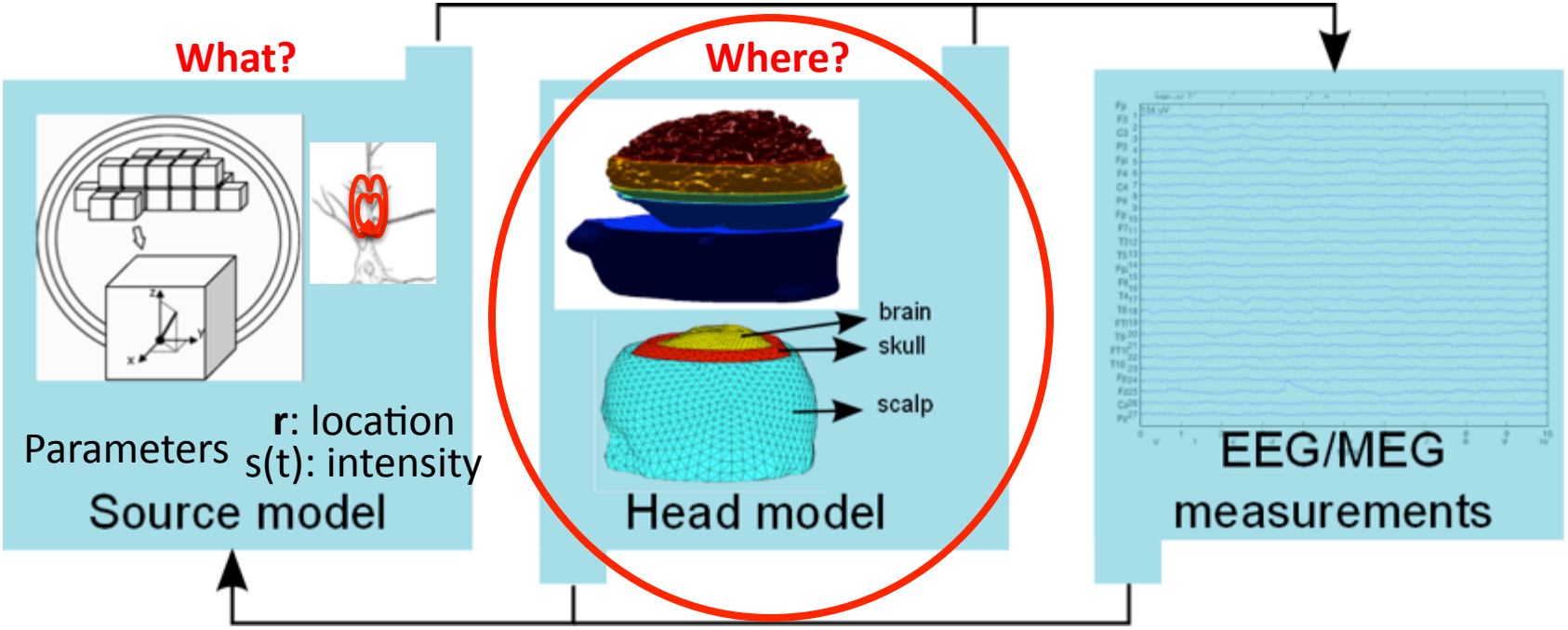
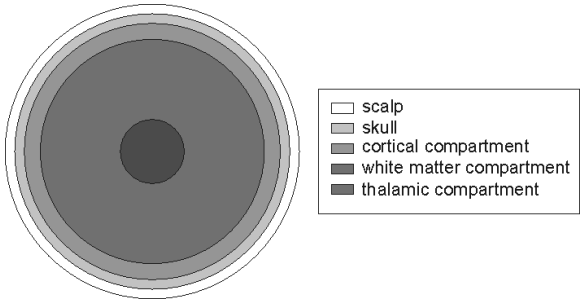



## Inverse problem **How?**

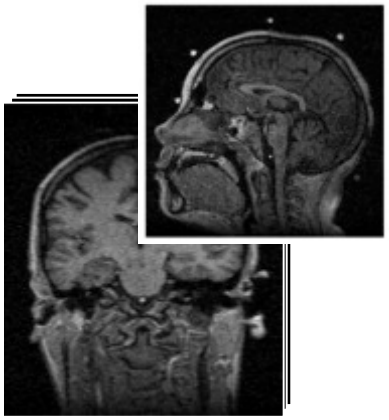
Estimation of the source parameters
given the EEG/MEG and a head model

# Volume conductor modeling

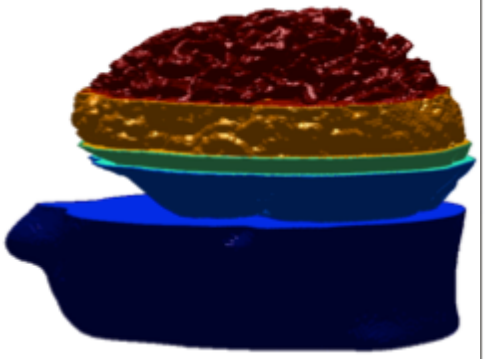
- Simplified spherical head models
  - Easy solution for forward problem

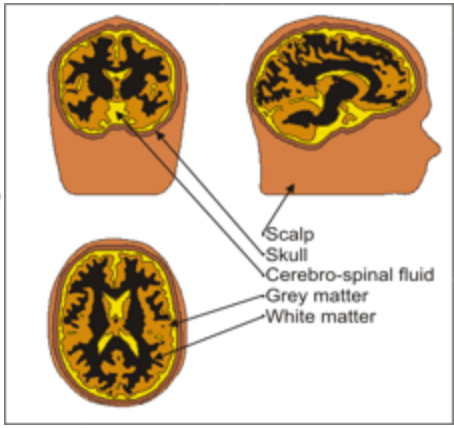



- Realistic head models



Segmentation

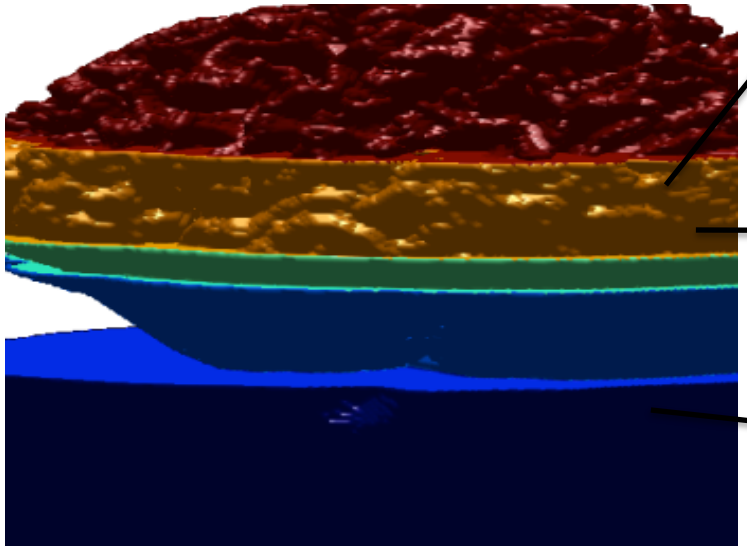




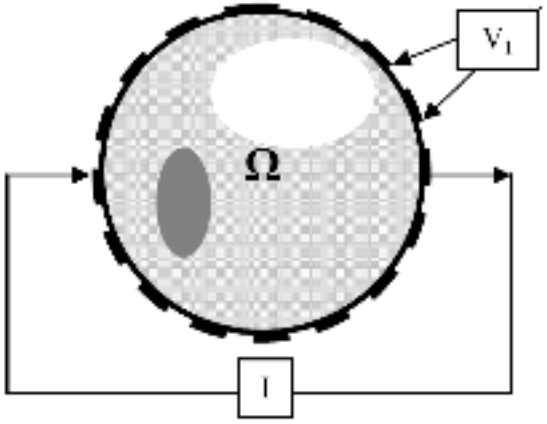

- Conductivities?

# Volume conductor modeling : conductivities

- Large uncertainty
  - Isotropic conductivities



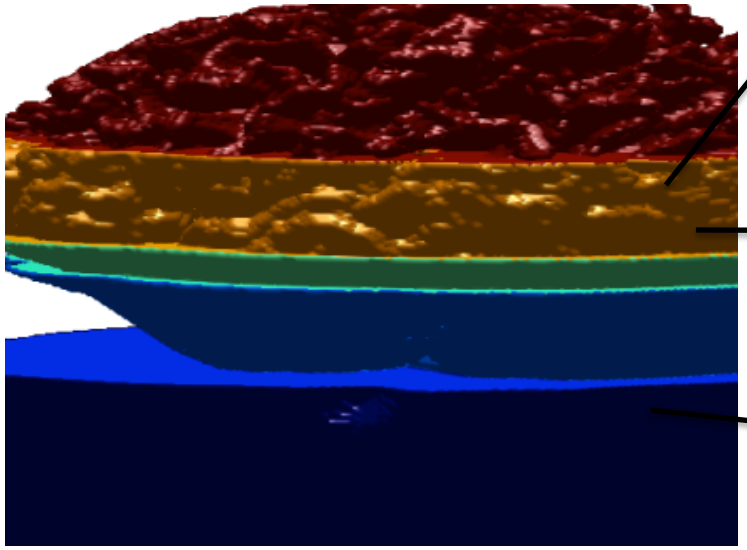

Electrical Impedance Tomography (EIT)

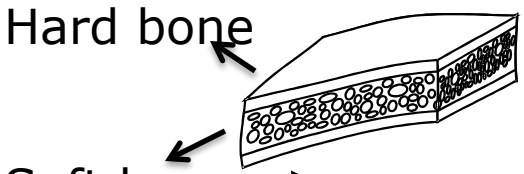


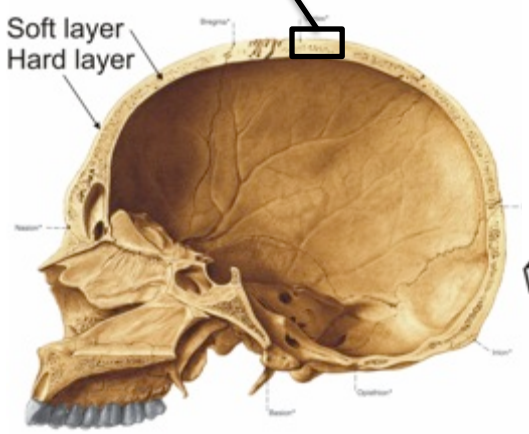

Magnetic Resonance - EIT

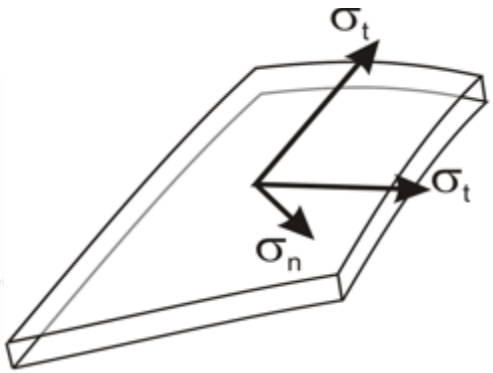
# Volume conductor modeling : conductivities

- Large uncertainty
  - Isotropic conductivities
  - Skull as anisotropic



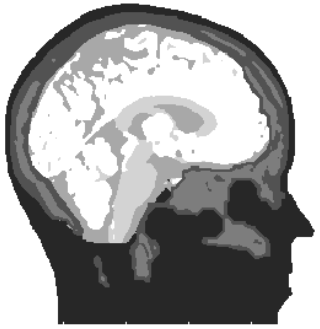



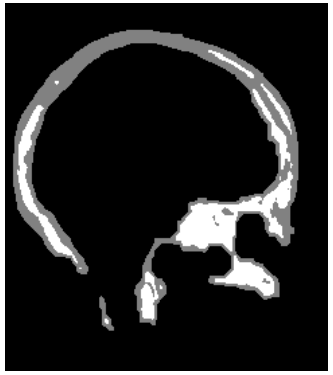




$$\frac{\sigma_{\text{tangential}}}{\sigma_{\text{perpendicular}}} = \frac{10}{1}$$

Skull as a layered conductor



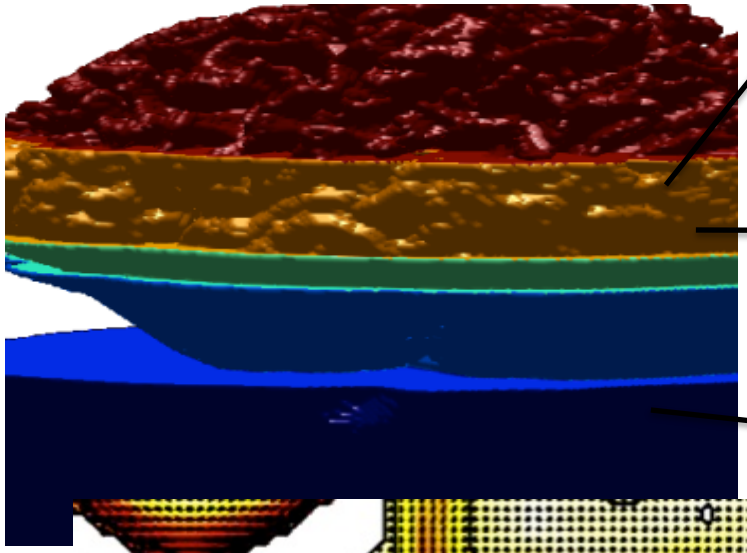


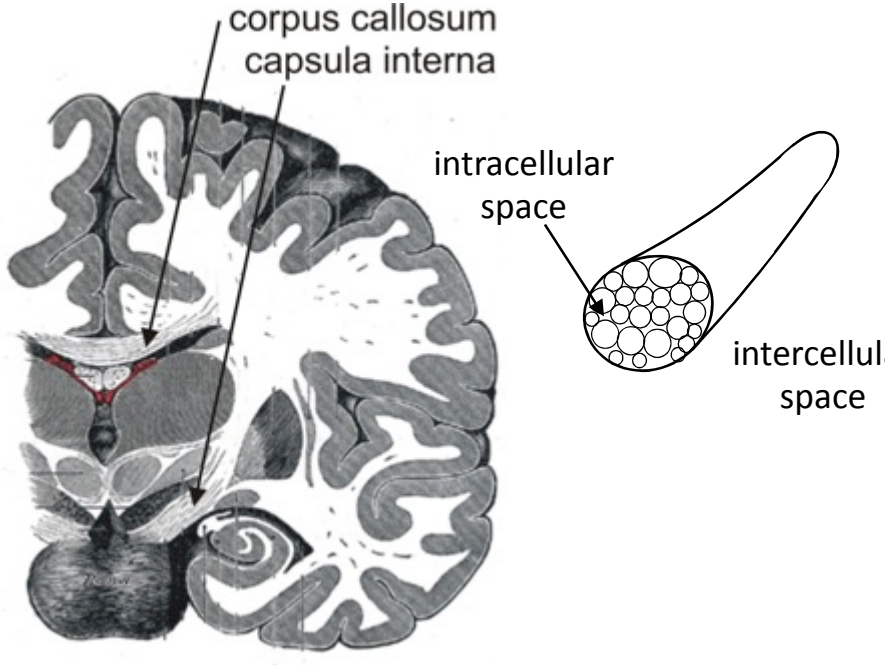
$$\frac{\sigma_{\text{tangential}}}{\sigma_{\text{perpendicular}}} = 1.8$$

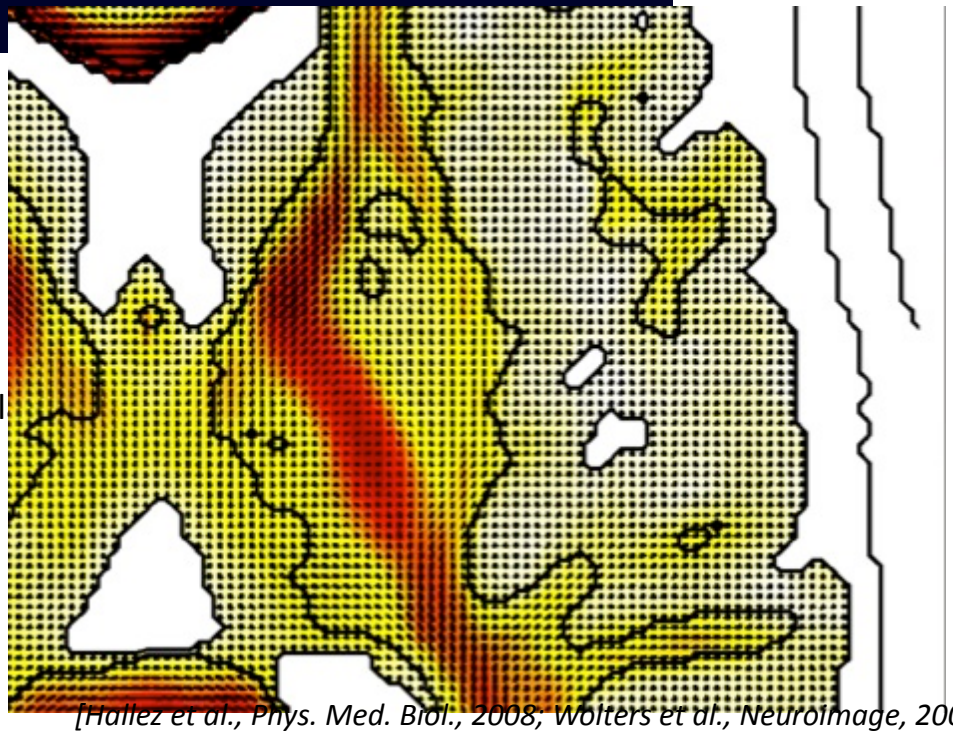
*[Montes et al., in preparation]*

# Volume conductor modeling : conductivities

- Large uncertainty
  - Isotropic conductivities
  - Skull as anisotropic
  - White matter nerve bundles as anisotropic

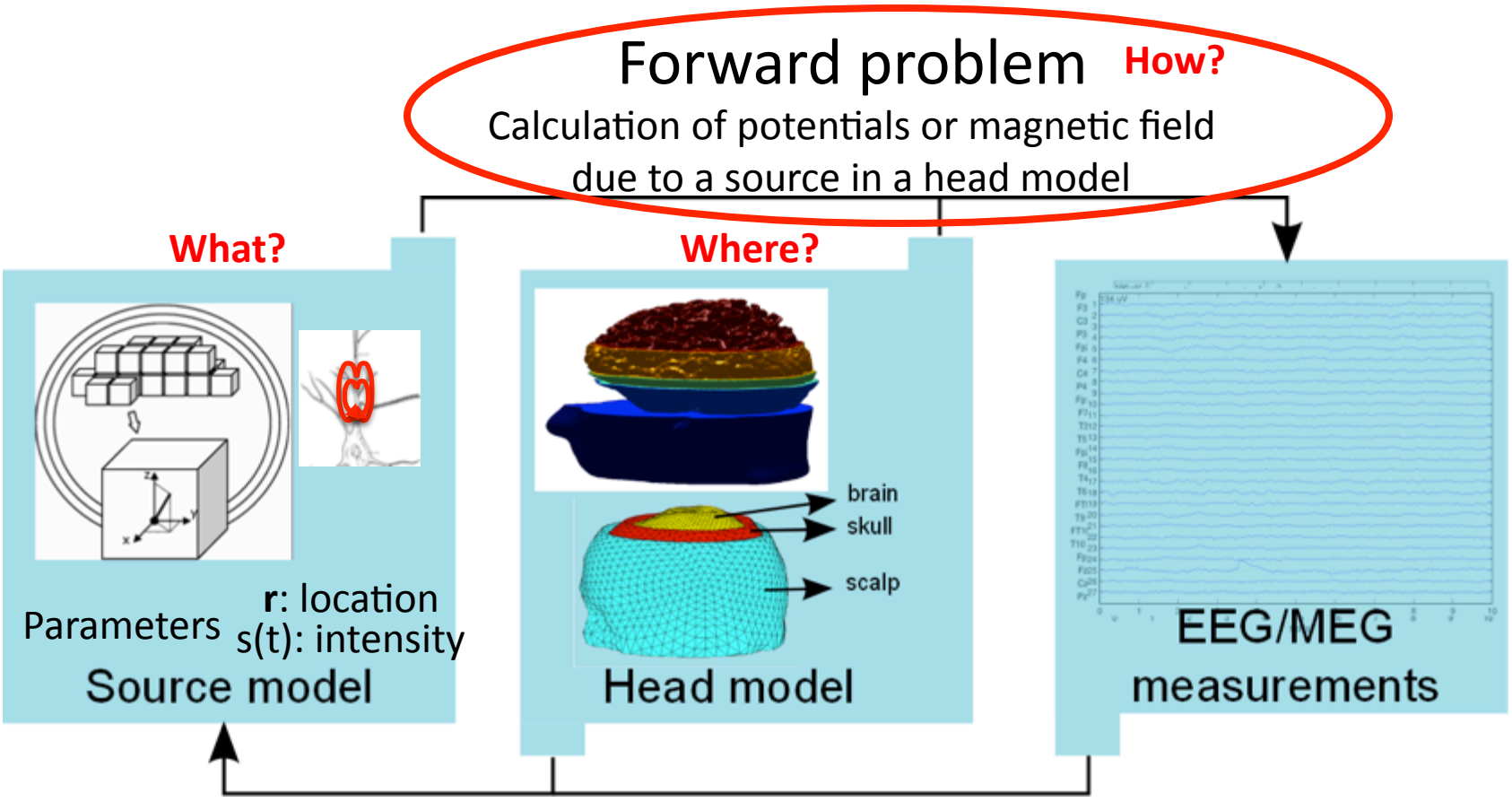


*[Hallez et al., Phys. Med. Biol., 2008; Wolters et al., NeuroImage, 2003]*

# EEG/MEG source localization



# Forward problem

- Calculation of the electrode potentials given the head model, electrode positions and the source

- Quasi-static approach

$$\nabla \cdot (\sigma(x,y,z) \cdot \nabla V(x,y,z)) = \nabla \cdot \mathbf{J}(x,y,z)$$

Maxwell's Equations

$\oiint \vec{E} \cdot \hat{n}\, dS = \frac{q}{\varepsilon_o}$ Gauss's Law

$\oiint \vec{B} \cdot \hat{n}\, dS = 0$ (no monopoles)

$\oint \vec{B} \cdot d\vec{l} = \mu_o \left( i + \varepsilon_o \frac{d}{dt} \Phi_E \right)$ and Ampère's Law

$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \Phi_B$ Faraday's Law

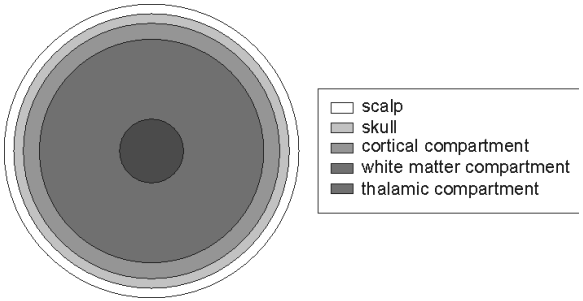
$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_o}$ $\quad \nabla \times \vec{B} = \mu_o \left( \vec{j} + \varepsilon_o \frac{\partial \vec{E}}{\partial t} \right)$

$\nabla \cdot \vec{B} = 0$ $\quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

(Differential Forms)

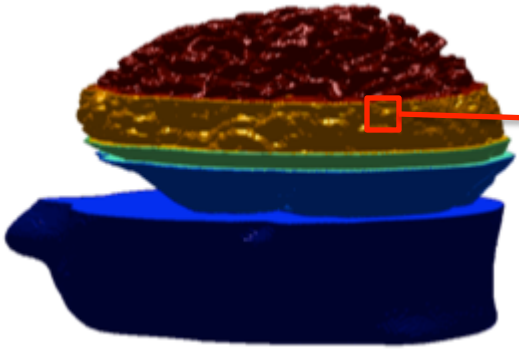
# Forward Problem

- Head model
  - Spherical head models
    - Analytical solution
    - Fast, but not realistic

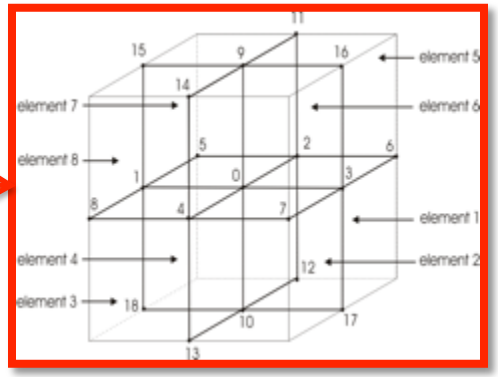



$$V(\mathbf{r}_{dip}, \mathbf{d}, \mathbf{r}_e) = \frac{d}{4\pi\xi_N r_e^2} \sum_{n=1}^{\infty} \frac{2n+1}{n} \left(\frac{r_{dip}}{r_e}\right)^{n-1} \left(f_n n \cos\alpha P_n(\cos\gamma) + g_n \cos\beta \sin\alpha P_n^1(\cos\gamma)\right)$$

  - Realistic head models
    - Numerical solutions
    - BEM, FEM, FDM



Potentials V are discretized into $\varphi$




$$\sum_{i=1}^{18} A_{ij} \varphi_j = \sum_{i=1}^{18} b_i$$

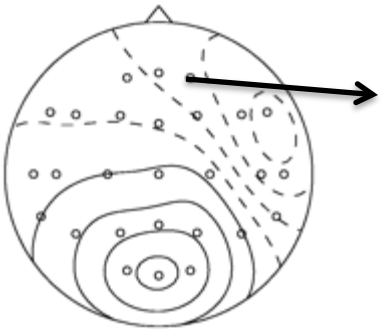
$$A\varphi = b$$

Linear system of equations of > 5 million equations

*[Hallez et al., Physics in Medicine and Biology 2005]*

# Forward Problem : spatio-temporal model

- Linearity of the Maxwell equations



$$v_{el}(t) = L(\mathbf{r}_d, \mathbf{r}_{el})\mathbf{e}_d s(t) = a(\mathbf{r}_d, \mathbf{r}_{el}, \mathbf{e}_d)s(t)$$

Intensity

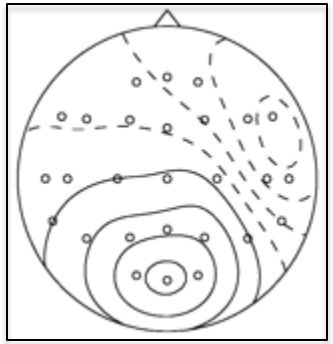
Lead-fieldmatrix non-linear wrt dipole location

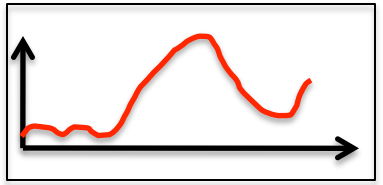
orientation

Contribution of a unitary dipole

Topography = potential distribution at the scalp on *p* electrodes

$$\mathbf{v}(t) = \begin{bmatrix} v_{el,1}(t) \\ \vdots \\ v_{el,p}(t) \end{bmatrix} = \begin{bmatrix} a(\mathbf{r}_d, \mathbf{r}_{el,1}, \mathbf{e}_d) \\ \vdots \\ a(\mathbf{r}_d, \mathbf{r}_{el,p}, \mathbf{e}_d) \end{bmatrix} s(t) = \mathbf{a}(\mathbf{r}_d, \mathbf{e}_d) \cdot s(t)$$

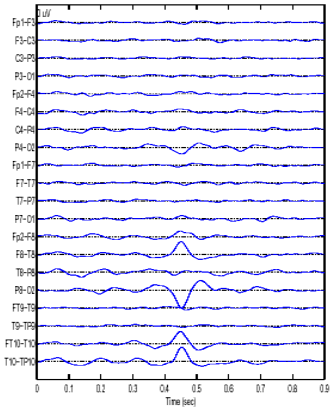




# Forward Problem : spatio-temporal model

- Linearity of the Maxwell equations

$$\mathbf{v}(t) = \mathbf{a}_1(\mathbf{r}_d, \mathbf{e}_d) \cdot s_1(t) + \mathbf{a}_2(\mathbf{r}_d, \mathbf{e}_d) \cdot s_2(t) + \dots$$



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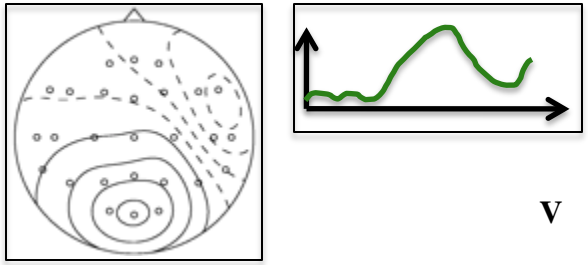
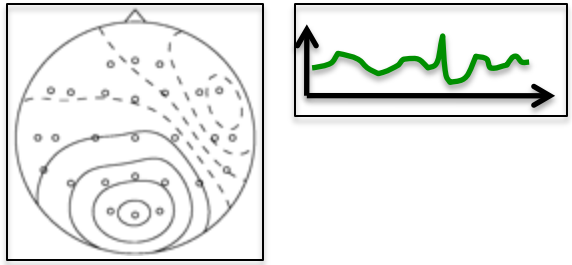


$\mathbf{v}$

+



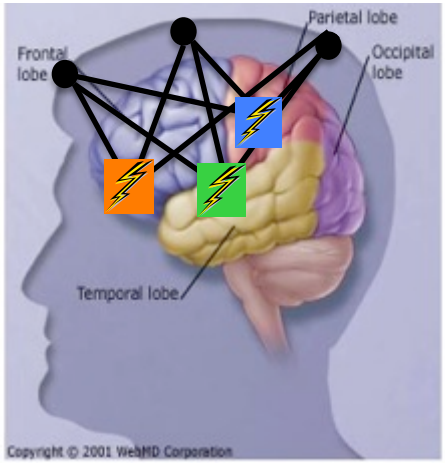
Spatio – temporal model

$$\mathbf{V} = \underbrace{\left[\mathbf{a}_1(\mathbf{r}_d, \mathbf{e}_d) \quad \dots \quad \mathbf{a}_p(\mathbf{r}_d, \mathbf{e}_d)\right]}_{\text{Topographies}} \underbrace{\begin{bmatrix} \mathbf{s}_1(t) \\ \vdots \\ \mathbf{s}_p(t) \end{bmatrix}}_{\text{Source signals}} = \mathbf{A}\mathbf{S}^T$$

# Intermezzo : decomposition methods

Spatio – temporal model

$$\mathbf{V} = \underbrace{\left[\mathbf{a}_1(\mathbf{r}_d,\mathbf{e}_d) \quad \dots \quad \mathbf{a}_p(\mathbf{r}_d,\mathbf{e}_d)\right]}_{\text{Topographies}} \underbrace{\begin{bmatrix}\mathbf{s}_1(t)\\ \vdots \\ \mathbf{s}_p(t)\end{bmatrix}}_{\text{Source signals}} = \mathbf{A}\mathbf{S}^T$$




Decomposition by *p* dipole sources

How to determine these:
See inverse problem

- Neurophysiological basis
- Model-driven: controllable

- Model driven : many a priori known parameters
- Number of sources

Source signals

- Decomposition by *m* signal sources
- Based on properties of time series
  - Blind source separation
  - PCA, ICA, CCA

- Data-driven : no need for a complecated head model
- Few parameters

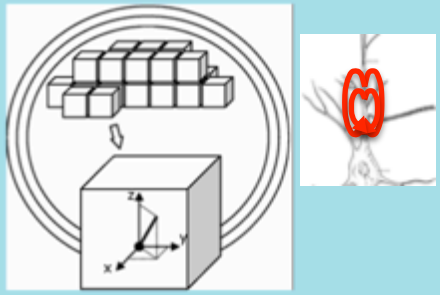
- Largely dependent on the data
- Sources should be stationary

# EEG/MEG source localization

## Forward problem **How?**

Calculation of potentials or magnetic field due to a source in a head model

**What?**

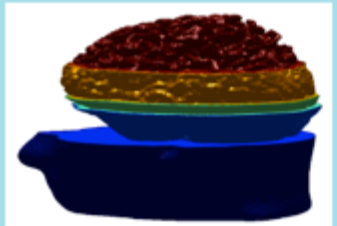


Parameters

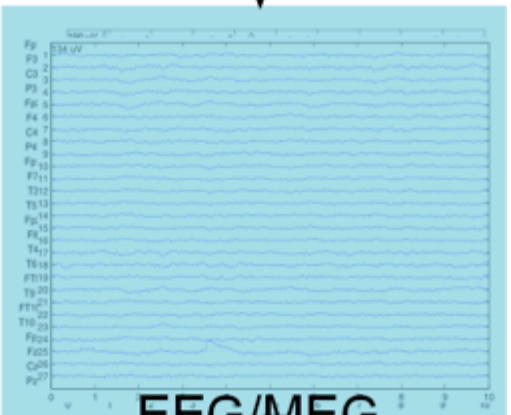
**r**: location
s(t): intensity

Source model

**Where?**




Head model



EEG/MEG measurements

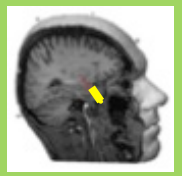
## Inverse problem **How?**

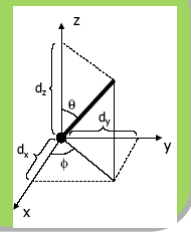
Estimation of the source parameters given the EEG/MEG and a head model

# Inverse problem

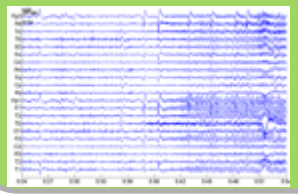
Patient

Source parameters $\boldsymbol{r}_d$ $\boldsymbol{e}_d$ $s(t)$

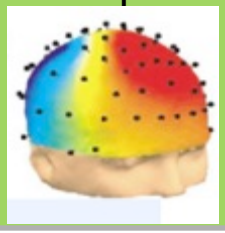


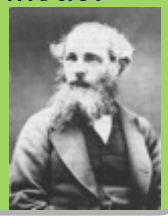



EEG measured : $\mathbf{V}_{meas}$



Forward problem : $\mathbf{V}_{model}$





Estimation of the parameters by means of minimization of a cost function

$$RE = \left\| \mathbf{V}_{meas} - \mathbf{V}_{model} \right\|$$

Spatio-temporal model

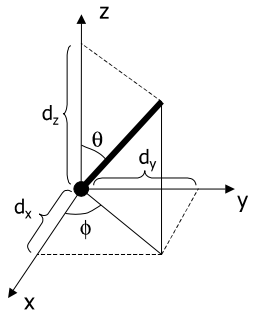
$$= \left\| \mathbf{V}_{meas} - \mathbf{A}\mathbf{S}^T \right\|$$

? Number of sources ?

# Inverse problem

$$RE = \left\| \mathbf{V}_{meas} - \mathbf{A}\mathbf{S}^{T} \right\|$$

**Assumption** : Within the EEG time frame there is only one source

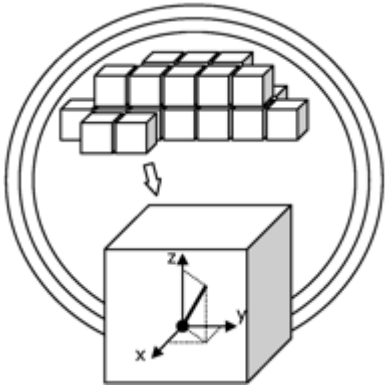



Single dipole model
- Location
- Orientation
- Intensity

**Overdetermined system**
- #parameters (=6) **<** #electrodes

**Least squares solution**
- Best fit of the model onto the measurements
- Time consuming

**Assumption** : there are many sources



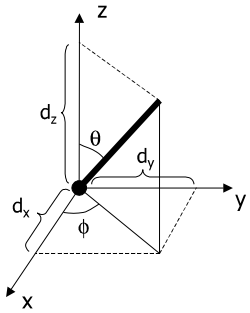

Distributed source model
- ≈ 10000 dipoles distributed of grey matter
- Intensity

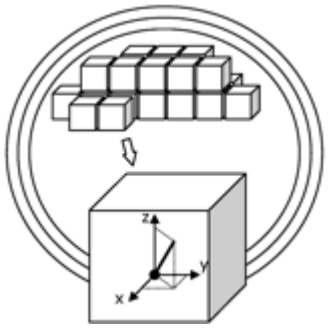
**Underdetermined system (ill-posed)**
- #parameters **>** #electrodes

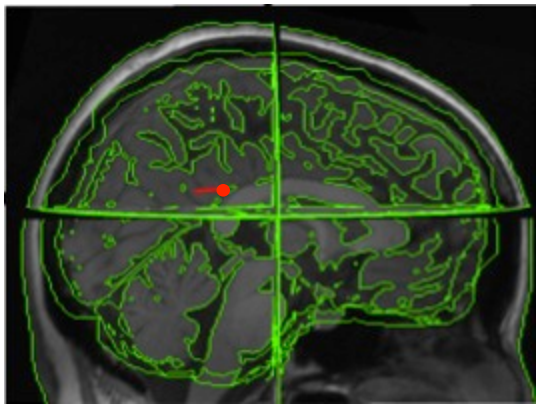
**Minimum norm solution**
- Fast
- Regularization

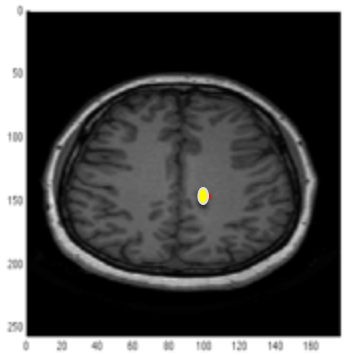
# Inverse problem

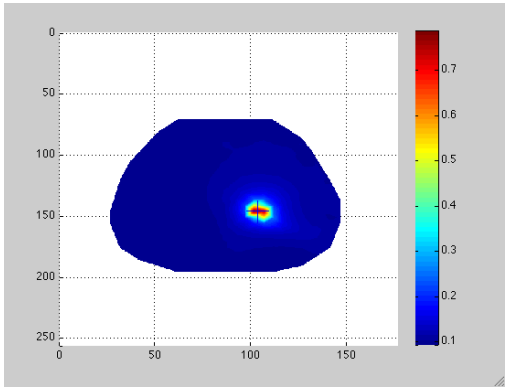
$$RE = \left\| \mathbf{V}_{meas} - \mathbf{A}\mathbf{S}^{T} \right\|$$









Parametric solution

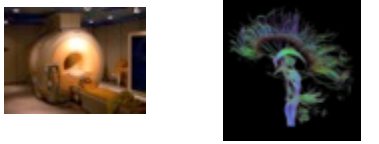
Imaging solution
MNE, (s)LORETA, FOCUSS, beamformers

MUSIC, RAP – MUSIC, POP – MUSIC
Multiple dipole localization (2 – 6 dipoles)

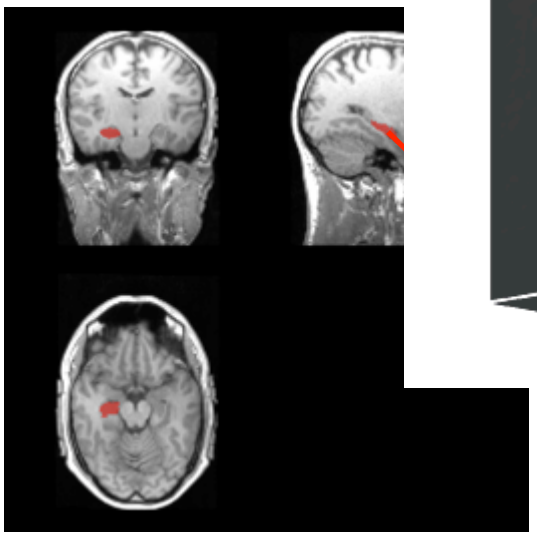
# Application: Localization of the epileptogenic zone

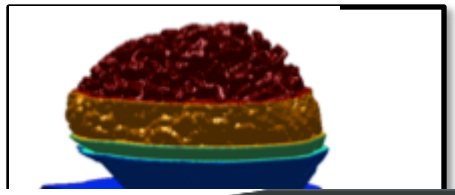
Model

Traditional MRI scan

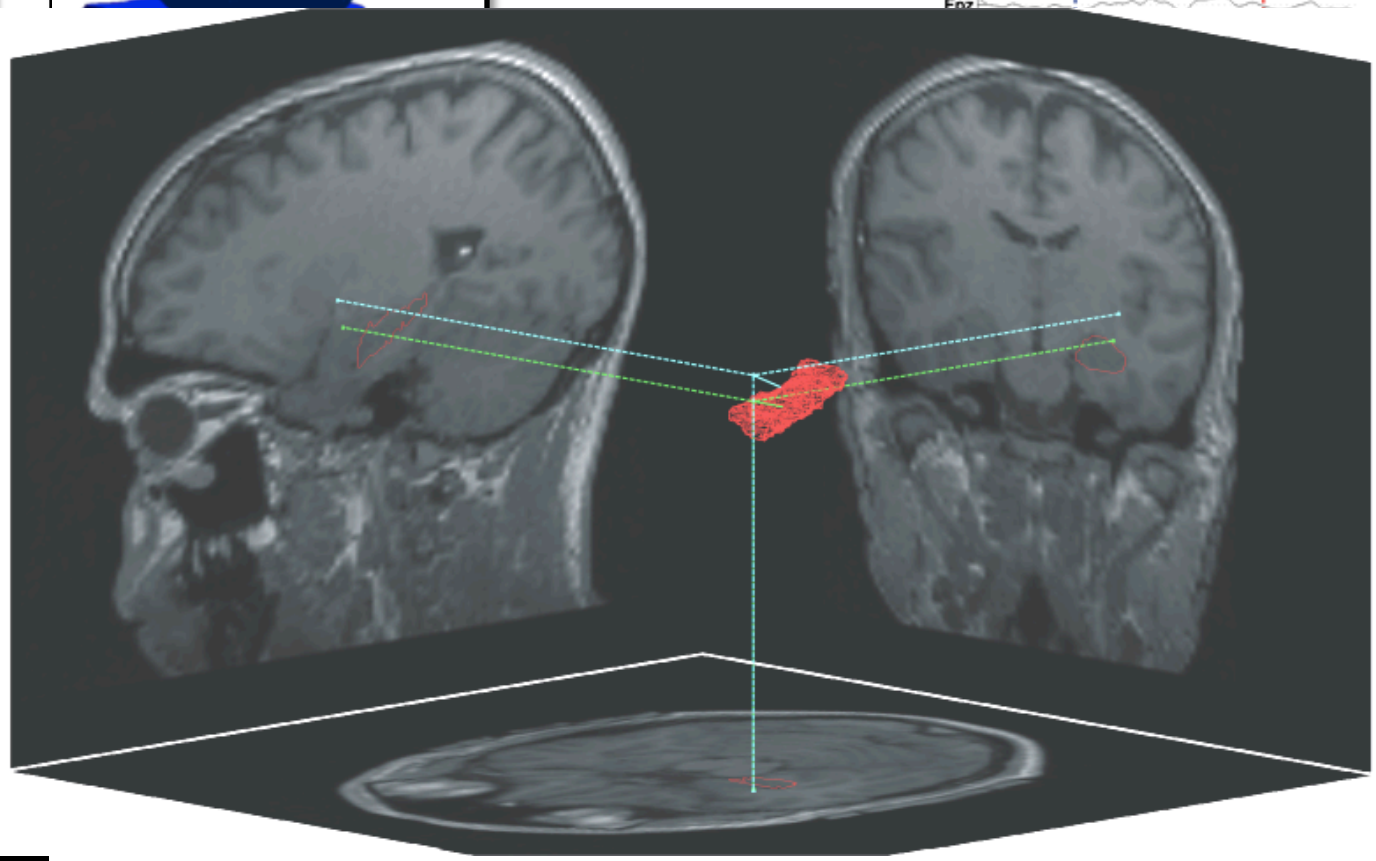


Diffusion weighted MRI





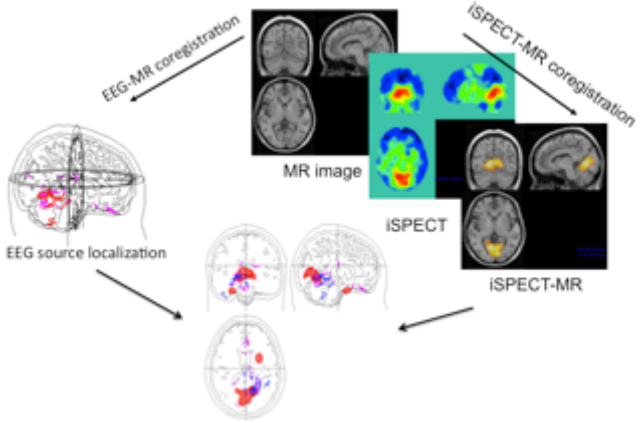
Measurements
Epileptic spike

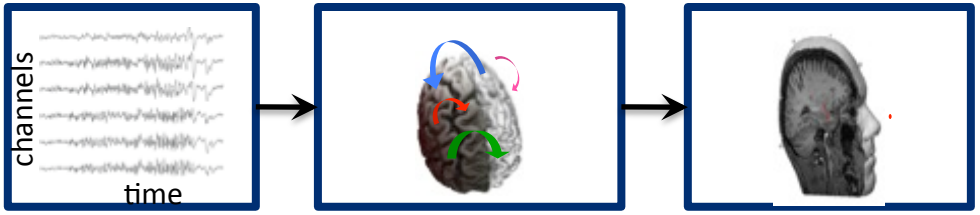
Estimation in head model with anistropic conductivities

Estimation in head model with isotropic conductivities

## Multimodality




## Connectivity

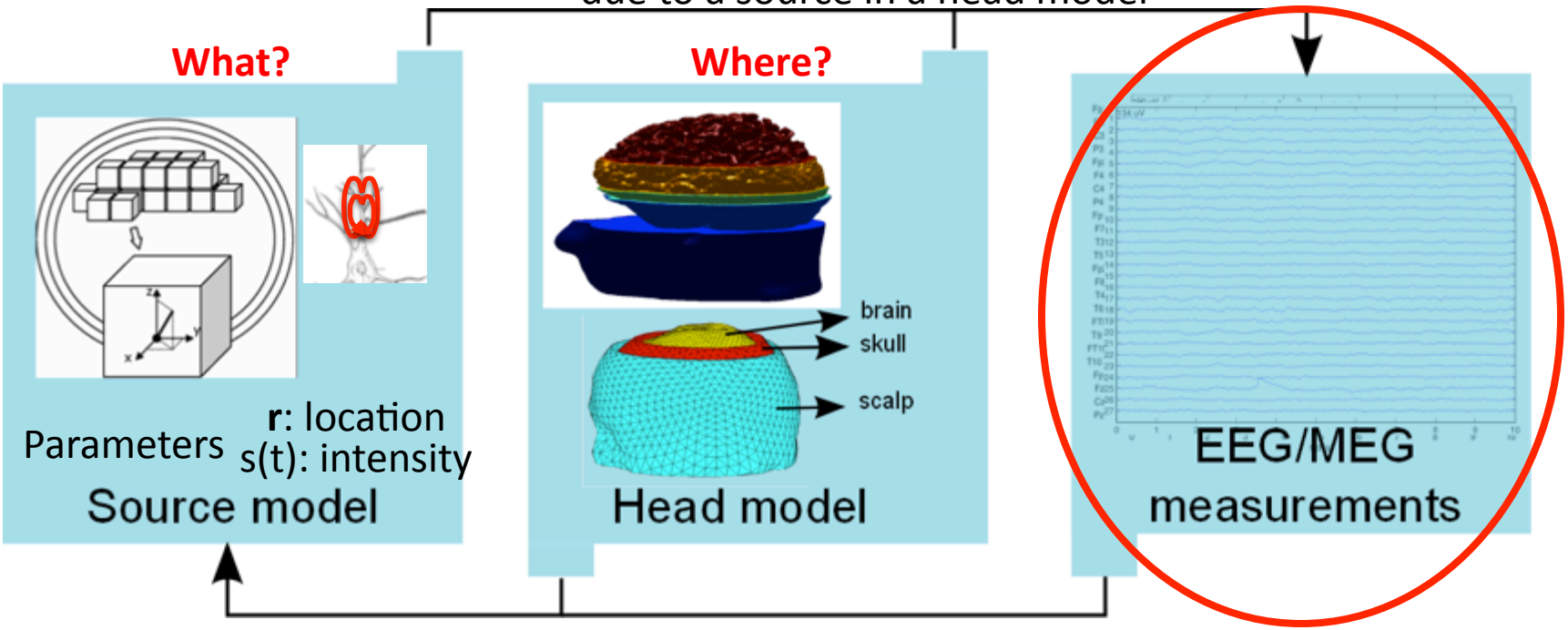



# RECENT TRENDS AND ADVANCES

# EEG/MEG source localization

## Forward problem **How?**

Calculation of potentials or magnetic field
due to a source in a head model

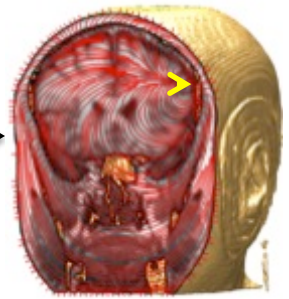


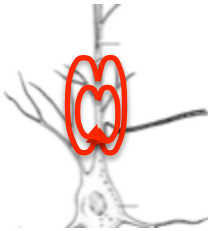

## Inverse problem **How?**

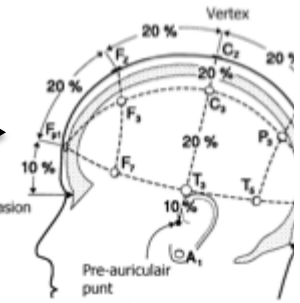
Estimation of the source parameters
given the EEG/MEG and a head model

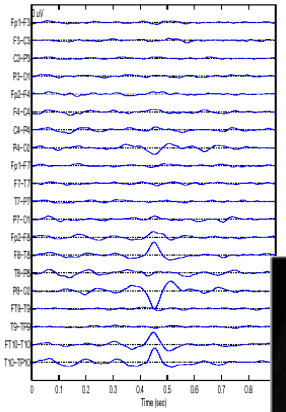
# Simultaneous EEG/MEG source localization

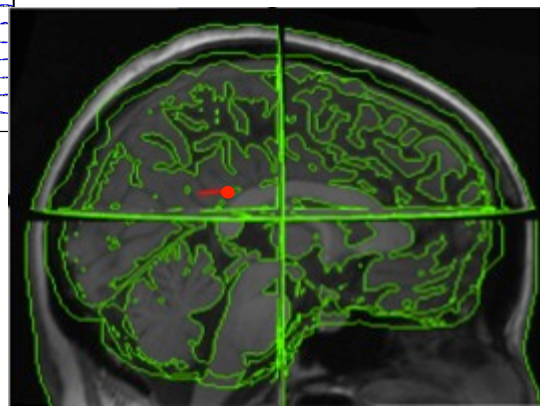
- EEG and MEG are generated by the same neuronal activity

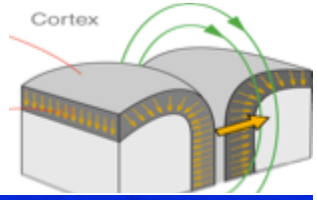


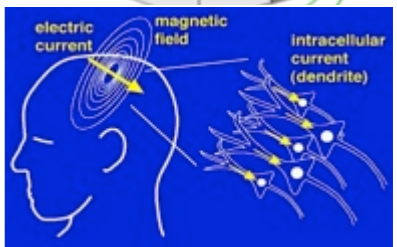


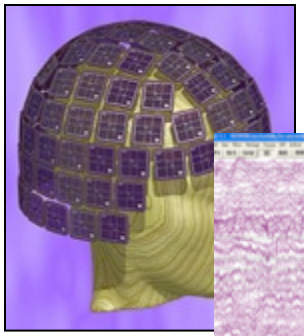


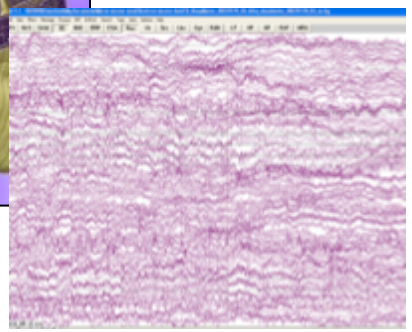









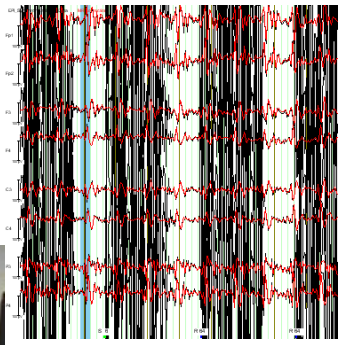
# Multimodal integration of EEG source localization

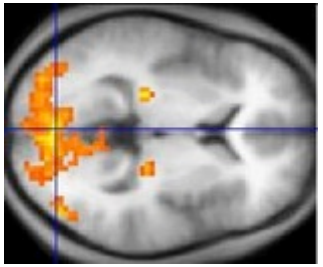
- Use functional imaging to improve spatial resolution of EEG source localization
  - Also provides timing information of the functional activation
  - A priori information of EEG source localization

Use functional MRI and EEG in epilepsy

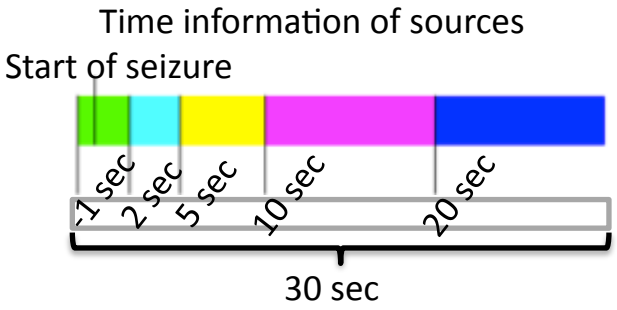
Preprocessing :

MR artefact
BCG artefact

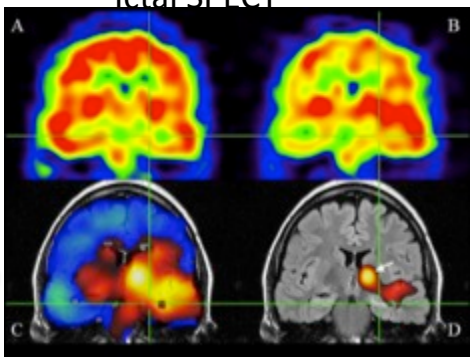




Use ictal SPECT for localization op epileptic seizures

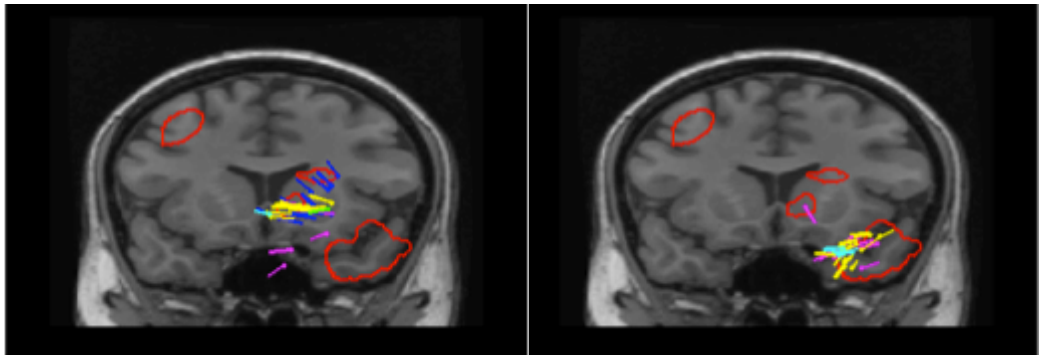



Ictal SPECT




Without integration

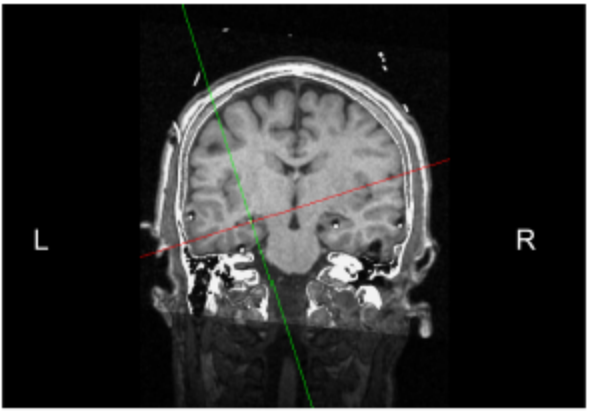
With integration

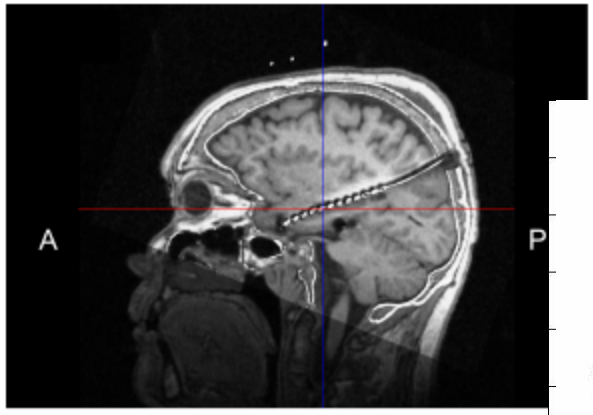


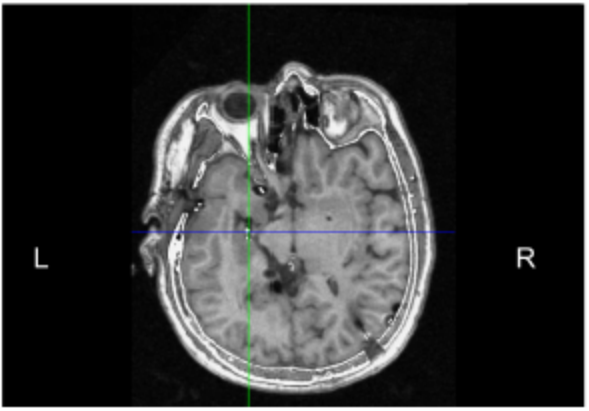
# Connectivity analysis

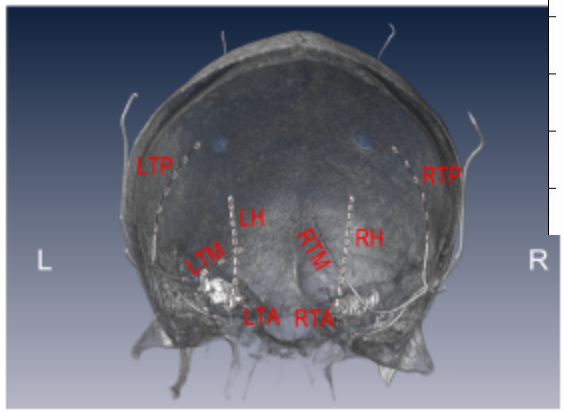
## Functional connectivity

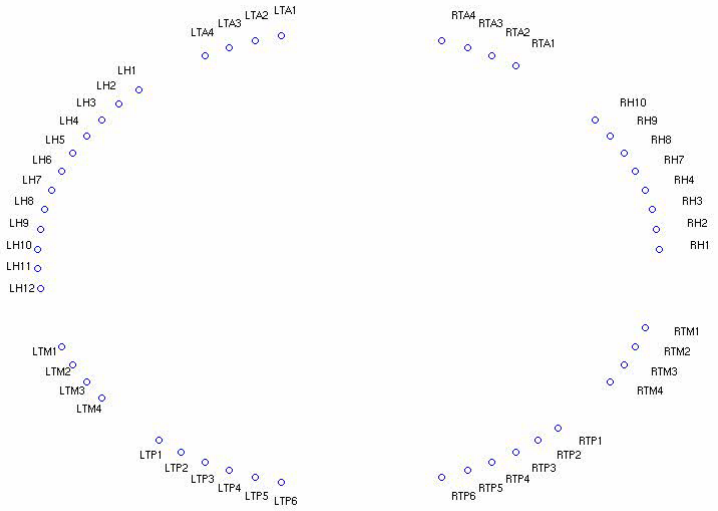
propagation pattern of information flow between signals

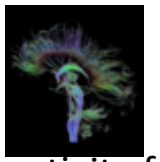


Use of functional connectivity in to **accurately estimate to onset zone** of an epileptic seizure

Correlation with structural connectivity from fibretracking

*[van Mierlo et al. 2010, Neuroimage, submitted]*

# Conclusions

- EEG and MEG can be used to investigate the electrophysiological activations in the brain
  - Adequate model (source, head model)
  - Link with anatomy

- Trends
  - combination of multiple modalities
    - to increase the resolution
    - to exploit the time information
  - Connectivity
    - visualize flow of information

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